Appendix 12-6: The Caloosahatchee Estuary: Status and Trends in Water Quality in the Estuary and Nutrient Loading at the Franklin Lock and Dam

The Caloosahatchee Estuary: Status and Trends in Water Quality in the Estuary and Nutrient Loading at the Franklin Lock and Dam

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Abstract

Nutrient loads delivered to the Caloosahatchee Estuary at the Franklin Lock and Dam (S-79) were calculated on an annual basis from 1982 – 2002. Monthly nutrient loads were also calculated and related to synoptic water quality samples taken in four different regions of the downstream estuary. Trends and status of estuarine water quality were also evaluated. Water quality data collection in the estuary has not been continuous. Three sampling periods were compared to establish trends (1985-1989, 1994-1996, 1999-2003). There were no trends in annual nutrient loads at S-79. These ranged from 938 to 5801 metric tons/yr for TN and 101 to 403 metric tons/yr for TP. In the down stream estuary color increased while total nitrogen and dissolved inorganic phosphorous decreased over time. The molar ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorous decreased. There was also evidence that the concentration of dissolved oxygen in bottom waters has declined in the upper and mid estuarine regions. Chlorophyll *a* may be an acceptable indicator of eutrophication in the Caloosahatchee system. In the lower estuary and San Carlos Bay, the concentration of chlorophyll increased with increasing loading of total nitrogen at S-79. In the Caloosahatchee Estuary, high concentrations of chlorophyll *a* were associated with low concentrations of dissolved oxygen at lags of one or two months. In San Carlos Bay chlorophyll *a* explained nearly 70 % of the variability in light attenuation, suggesting that increased nutrient loading could reduce light available to seagrasses. Empirical relationships between (1) nutrient loading at S-79 and chlorophyll *a* concentrations in San Carlos Bay and (2) light extinction and chlorophyll *a* in San Carlos Bay in combination with assumptions about light requirements for seagrass were used to calculate nutrient loads at S-79 that were commensurate with growth of seagrass at various depths.

Chlorophyll a is a good indicator of nutrient enrichment in the Calooshatchee estuary and San Carlos Bay.

Introduction:

Excessive fertilization or eutrophication of coastal waters with nitrogen and phosphorus is a continuing world wide problem (Palmer et al. 2004; Smith et al 2003; Cloern 2001; Eyre 2000). Conceptual understanding of the responses of coastal ecosystems to eutrophication has changed. Cloern (2001) describes three phases in the evolution of this concept. The first emphasized the link between nutrient input, enhanced production of phytoplankton biomass, and the subsequent depletion of dissolved oxygen (Shindler 1975; Ryther and Dunstan 1971). The second phase recognizes that there are a variety of direct responses and these can lead to a variety of indirect responses. A good example is the decline of seagrass associated with eutrophication. Increased nutrient supplies lead to increased chlorophyll biomass in the water column (a direct response) that shades out submerged aquatic vegetation (an indirect response, Twilley et al. 1985). Diversity of response is also explained in part by system specific physical and biological attributes or “filters” such as tidal range (Monbet 1992), residence time (Nixon et al 1996), and dense populations of filter feeders (Officer et al 1982; Meeuwig et al 1998). These attributes confer a proclivity for the system to respond in one way or another (Cloern 2001). Understanding how these filters work and how they interact with other stressors is central to the development of the next (Phase III) conceptual model of eutrophication.

One important and virtually unexplored interaction is between eutrophication and human induced changes in freshwater input to estuaries and other coastal ecosystems (Cloern 2001). Two major forces are reshaping freshwater inflows to estuaries: demographics and engineering (Montagna et al. 2002). Nearly 60 % of the people in the United States live within 60 km of the coast and 17 of the 20 fastest growing counties are located in coastal areas (Culliton, 1998). The hydrology of nearly every major river in the contiguous U.S. has been modified by dams, diversions, and withdrawals (Naiman et al. 1995). Such alterations can have pronounced effects on the magnitude and composition of nutrient loads and the subsequent processing of these materials in coastal systems (see Cloern, 2001 for examples). The engineering of coastal systems has had documented effects on their ecology including: increased algal biomass, shifts in phytoplankton species, losses of mangroves and destruction of nursery habitats for marine fishes. The consequences of reversing these effects through additional engineering projects remain largely uninvestigated.

The Caloosahatchee River and Estuary located on the southwest coast of Florida (Figure 1), comprise a system that has been high altered from its natural state by human intervention and engineering. The Caloosahatchee River runs 67 km from Lake Okeechobee to the Franklin Lock and Dam (S-79). S-79 separates the freshwater river from the estuary that terminates 40 km downstream at Shell Point (Figure 1).

Modification of the Caloosahatchee River watershed to accommodate citrus groves, sugar cane, cattle grazing and urban development has changed patterns of storm water runoff. Retention and storage have been lost higher volumes and peak flows now characterize runoff events. The system has been altered in other ways as well. The river has been

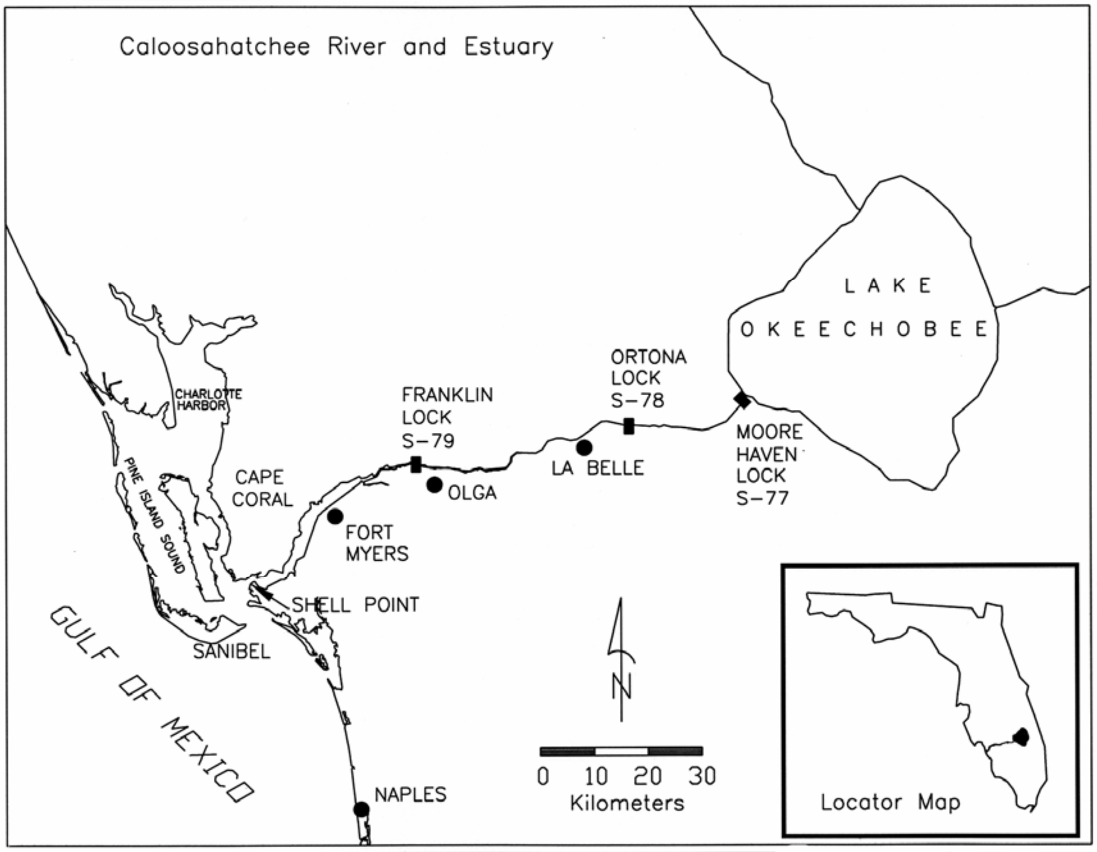

Figure 1. Location of the Caloosahatchee River and Estuary.

straightened, deepened and three water control structures have been added. The last, S-79, was completed in 1966 to act in part as a salinity barrier (Flaig and Capece 1988). The River has also been artificially connected to Lake Okeechobee to convey regulatory releases of water to tide.

The estuarine portion of the system has also been modified. Seven automobile bridges and one railroad bridge connect the north and south shores of the estuary. A navigation channel has been dredged and in the 1960's a causeway was built across the mouth of San Carlos Bay. Historic oyster bars upstream of Shell Point have been mined and removed to be used in the construction of roads.

Delivery of freshwater to the estuary at S-79 has been altered and is more variable with higher wet season discharges and lower dry season discharges. The over abundance of freshwater during the wet season can flush all salt from the estuary. By contrast, inflow at S-79 can stop entirely during the dry season. Saltwater intrudes up to S-79, sometimes reaching 10 – 15 ppt leading to truncation of the salinity gradient.

The engineering solution is to construct more storage in the Caloosahatchee watershed with the intention of reducing the frequency of high flows and providing freshwater to the estuary during the dry season. As part of the Comprehensive Everglades Restoration Plan (CERP) several reservoirs are contemplated. These will store water during the wet season, thereby reducing high flows and release it during the dry season thereby providing a minimal freshwater inflow. When all CERP projects are completed, models predict a 40% reduction of freshwater discharge at S-79.

The response of the Caloosahatchee Estuary to nutrient loading and how that response might change as contemplated hydrologic modifications are implemented requires investigation. Scientifically such issues should be considered within the context of our more complex understanding of eutrophication (Phase II, Cloern 2001) From a management perspective such questions are important because water delivered to the natural system by CERP projects must meet applicable water quality standards (WRDA, 2000).

In this report, water quality data collected by the South Florida Water Management District in the Caloosahatchee Estuary and San Carlos Bay are analyzed statistically. The objectives of the analysis are to (1) summarize the current status and trends in estuarine water quality and nutrient loading from S-79, (2) assess potential symptoms of eutrophication in the Caloosahatchee Estuary and (3) evaluate the use of chlorophyll *a* as an indicator of excess nutrient loading.

Methods:

Data Sets:

The data used to evaluate status and trends in water quality in the estuary and nutrient loading at S-79 came from five (5) monitoring programs. All programs monitored the quality of surface waters with samples being taken within the top 0.5 meter of the water column.

CR: The Caloosahatchee River (CR) program sampled just upstream of the Franklin Lock and Dam (S-79). The program began in January, 1981 and continues to the present. Data from 1981 through June 2003 were analyzed. The frequency of sampling varied through out the period of record generally being 6 – 8 times per year but ranging from 3 to 12 (monthly) times per year.

CAL: The Calooshatchee Estuary program sampled water quality at 17 stations in the estuary (Shell Point to S-79), San Carlos Bay, Matlacha Pass, and Pine Island Sound. The stations, sampled monthly from 12/85 to 5/89, were all located downstream of S-79.

CALHF: The Caloosahatchee Estuary High Flow effort sampled monthly at 8 stations from 10/94 to 8/96. Seven stations were located in the estuary and San Carlos Bay, while one was located in freshwater upstream of S-79.

CES: The Center for Environmental Studies program sampled 7 stations in the estuary (S-79 to Shell Point) and one (1) station upstream of S-79 on a monthly basis from 4/1999 to 3/2002. As of 5/2002, the number of stations was reduced to 4, with one upstream of S-79 and the rest in the downstream estuary. This reduced sampling effort continues to the present. Data through June 2003 were used in the analysis.

SERC: Southeastern Environmental Research Center program sampled 8 stations in San Carlos Bay, Pine Island Sound, Matlacha Pass and the Gulf of Mexico on a monthly basis beginning in January 1999. The project continues to the present. Data to through March 2003 were used in the analysis.

ERD: The Environmental Research and Design Program sampled 15 sites in the Caloosahatchee Estuary. This program was not designed to detect long term trends and therefore was not used in the analysis of water quality trends or loading. Stations were sampled for two month long periods in each of three years (2000, 2001, and 2002). Each year one wet season month and one dry season month was sampled. During each sampling month, estuarine stations were occupied 4 times, once every ten days.

Calculation of Nutrient Loads at S-79

The load of nutrients delivered to the estuary at the Franklin Lock and Dam (S-79) was calculated by multiplying the daily average discharge of freshwater by the concentration of nutrients in the water. A daily average discharge at S-79 was available from records kept by the SFWMD dating back to the 1960s. Data taken upstream of S-79 from the CR, CALHF and CES programs were used to generate a data set of daily concentrations by linear interpolation between sampling dates. From these data daily, 30-day and annual loads were calculated.

Analysis of loads at S-79 concentrated on temporal trends and sources of variation in the load (concentration or discharge). Temporal trends in annual discharge and loads of total nitrogen and phosphorus from 1891 to 2002 were evaluated using Kendall's Tau b correlation coefficient (SAS, 1989). Trends in daily loads were evaluated as follows. Only loads calculated for days upon which a concentration at S-79 was actually measured were considered. Daily load and concentration data were averaged by year and month to avoid undue influence of any time period. This procedure yielded a daily average load for each month in which S-79 was sampled. Temporal trends were evaluated both with Kendall's Tau b and Spearman's Rank correlation coefficients (SAS 1989). Multiple regression was employed to evaluate the contribution of discharge and concentration to variation in daily load.

Water Quality in the Estuary: Trends

Water quality varies in both time and space. In order to account for spatial variation, the Caloosahatchee system was divided into 4 areas (Figure 2) each encompassing stations from the various sampling programs summarized above (Table 1). Only data from the CAL, CALHF, CES and SERC programs were used to evaluate trends in water quality. To account for potential differences in detection limits, the detection limits for the CAL program were applied to all data. Values less than the CAL detection limits were set to one half the detection limit.

In each region data were sorted by year and month and then averaged across stations. This produced set of monthly observations in each region. Unfortunately the data were discontinuous, precluding traditional time series analysis. Rather the data fell into 3 time periods: December 1985 – May 1989 (CAL), November 1994 – August 1996 (CALHF) and April 1999 – June 2003 (CES, SERC).

Table 1. Sampling stations in the four regions of the Caloosahatchee Estuarine System.

	Program			
Region of Estuary	CAL, CALHF	CES	SERC	ERD
Upper	01, 02, 03, 04	03,04	-	12,13
Mid	05,06,07,08	05,06	-	9,10,11
Lower	09,10,17	07,08	474	6,7,8
San Carlos Bay	18,11,12,13	-	472,472	3,4,5

Statistically data from each region differences between time periods were evaluated with the Kruskal-Wallis H test (NPAR1WAY, SAS 1989). This test amounts to a non-parametric one way analysis of variance on ranked data with period being the treatment factor. If the H test was statistically significant, data were ranked within each region and differences between individual periods were evaluated using Proc Multtest, with a bootstrap correction of the p-value to account for making multiple t-tests on ranks (equivalent to a Wilcoxon rank-sum test). To evaluate overall regional differences data from all periods were combined, ranked within region and analyzed as above.

Other standard correlation and regression techniques applied to the data are described in the results section. All statistical analyses were performed using SAS Version 8 software.

Water Quality in the Estuary: Status

The status of water quality in the Caloosahatchee was assessed through comparison with State of Florida standards and the impaired water body rule. Dissolved oxygen was compared to the State standard of 4.0 mg/l for Class III primarily marine waters and the chlorophyll standard (11 μg/l) for impaired estuarine waters. An estuary is said to be impaired if the annual mean chlorophyll concentration is greater that 11 ug/l.

Water Quality in the Estuary: Loading at S-79

The dependence of nutrient and chlorophyll *a* concentrations in the estuary on loading at S-79 was established by simple linear correlation. Data from stations within each region were averaged by sampling date to produce one observation per region per date. Correlations between concentration in the estuary and the loading that had occurred over the 30 days prior to sampling were calculated.

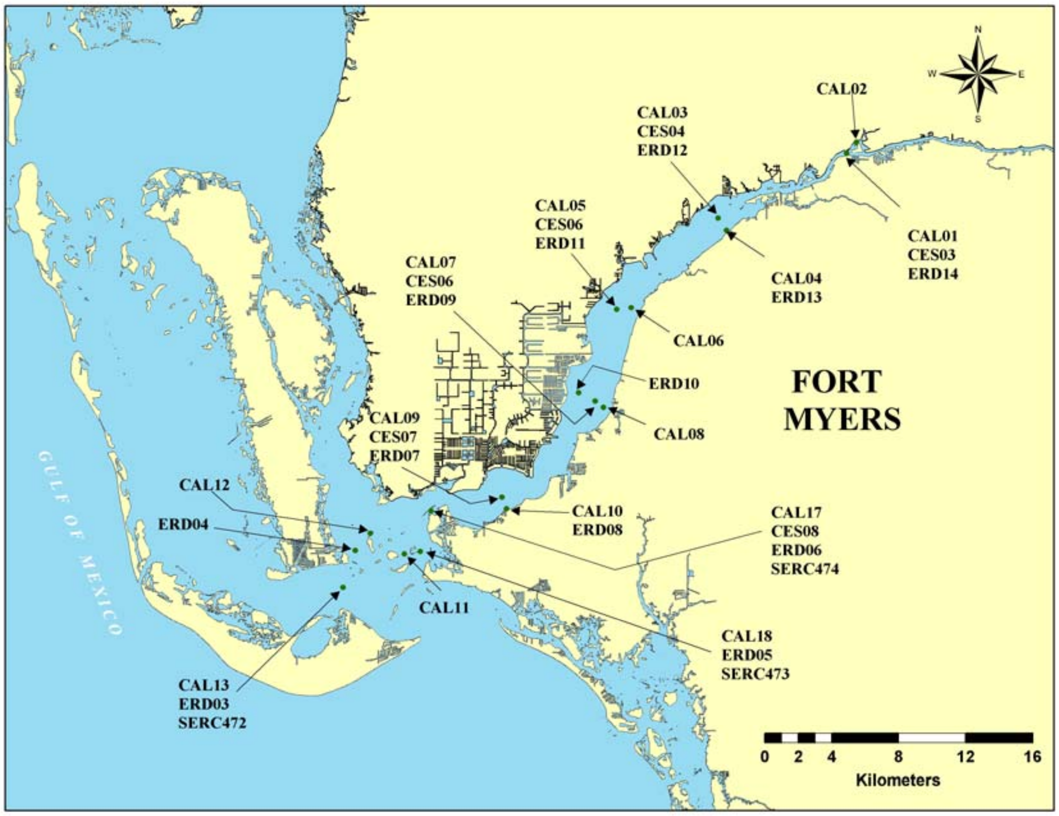

Figure 2. Location of water quality sampling stations in the Caloosahatchee Estuary and San Carlos Bay.

Results:

Nutrient Loading:

Annual discharge of freshwater at S-79 averaged 1.27 million acre-ft per year, with a minimum of 424 thousand ac-ft in 1990, a drought year and 3.38 million ac-ft in 1995 a very wet year (Figure 3). No long term trend in discharge was detected (Kendall Tau b, $p>0.60$) Annual loading of total nitrogen at S-79 averaged 2412 metric tons/year with a minimum of 938 metric tons in 1990 and a maximum of 5801 metric tons in 1995. Over the period 1981 through 2002 there was no general increase or decrease in the annual total nitrogen load ($p>0.8$). Loading of total phosphorus averaged 220 metric tons/year with a minimum of 101 metric tons in 1990 and a maximum of 403 metric tons in 1992. No long term trends were detected ($p>0.8$). The molar ratio of the total N load to the total P load averaged 24.4 and ranged from 12 to 37.

Variation in daily nutrient loads at S-79 was primarily a function of freshwater discharge (Table 2). In multiple regressions, this variable explained between 50 and 90 % of the variation in nutrient loads. Concentration explained a significant but substantially smaller proportion of the total variation (range 2 – 26 %).

Table 2. Fraction of variation in loading at S-79 explained by fluctuations in discharge and nutrient concentration. All fractions are statistically significant at $p<0.0001$.

	Discharge	**Concentration**	**Total Variation**
Total Nitrogen (TN)	0.908	0.023	0.931
Dissolved Inorganic Nitrogen (DIN	0.692	0.082	0.774
Total Phosphorus (TP)	0.716	0.117	0.833
Dissolved Inorganic Phosphorus(DIP)	0.503	0.260	0.763

No long term trends in the daily loads (Table 3) of total nitrogen, total phosphorus, dissolved inorganic nitrogen or dissolved inorganic phosphorus at S-79 were detected. While no trend in the loading of total nitrogen was detected, the concentration did show a slight long term decrease (Figure 4). The composition of the total load also appeared to change with the fraction of dissolved inorganic nitrogen increasing from about 18 % in 1981 to about 25 % in 2002. The molar N to P ratio of the total daily load averaged nearly 30 and the median was 26. The molar ratio of the daily inorganic load averaged about 9.5 over the 22 year period of record with a median of 7.5.

Table 3. Summary of daily loads at S-79

	Daily Load (kg/day)			
	Mean	**Median**	**Minimum**	**Maximum**
Total Nitrogen	7018	2618	0	46,885
Dissolved Inorganic Nitrogen	1385	567	0	12,874
Total Phosphorus	657	253	0	5,141
Dissolved Inorganic Phosphorus	426	157	0	3,352

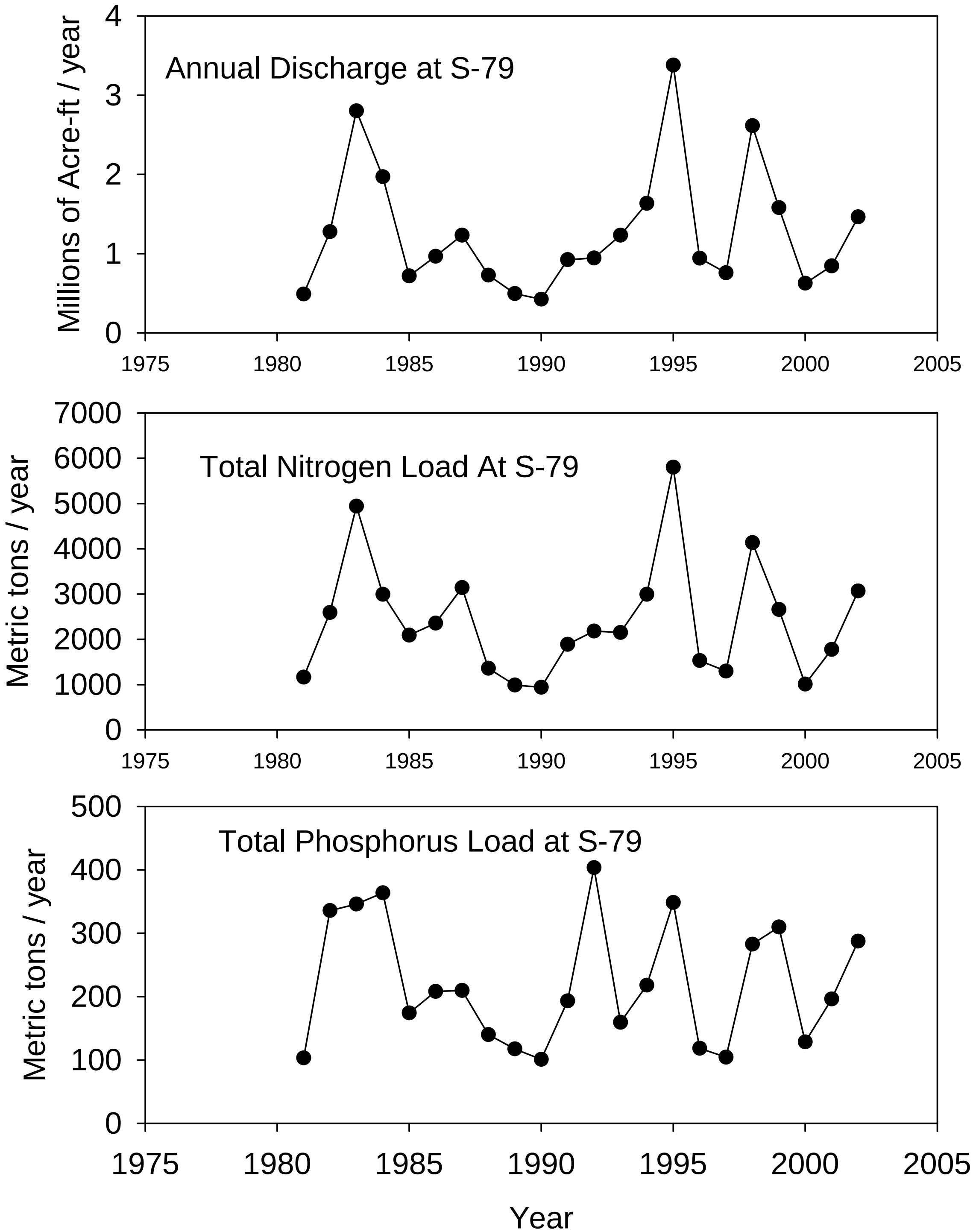

Figure 3. Annual discharge and annual loading of total nitrogen and phosphorus at S-79

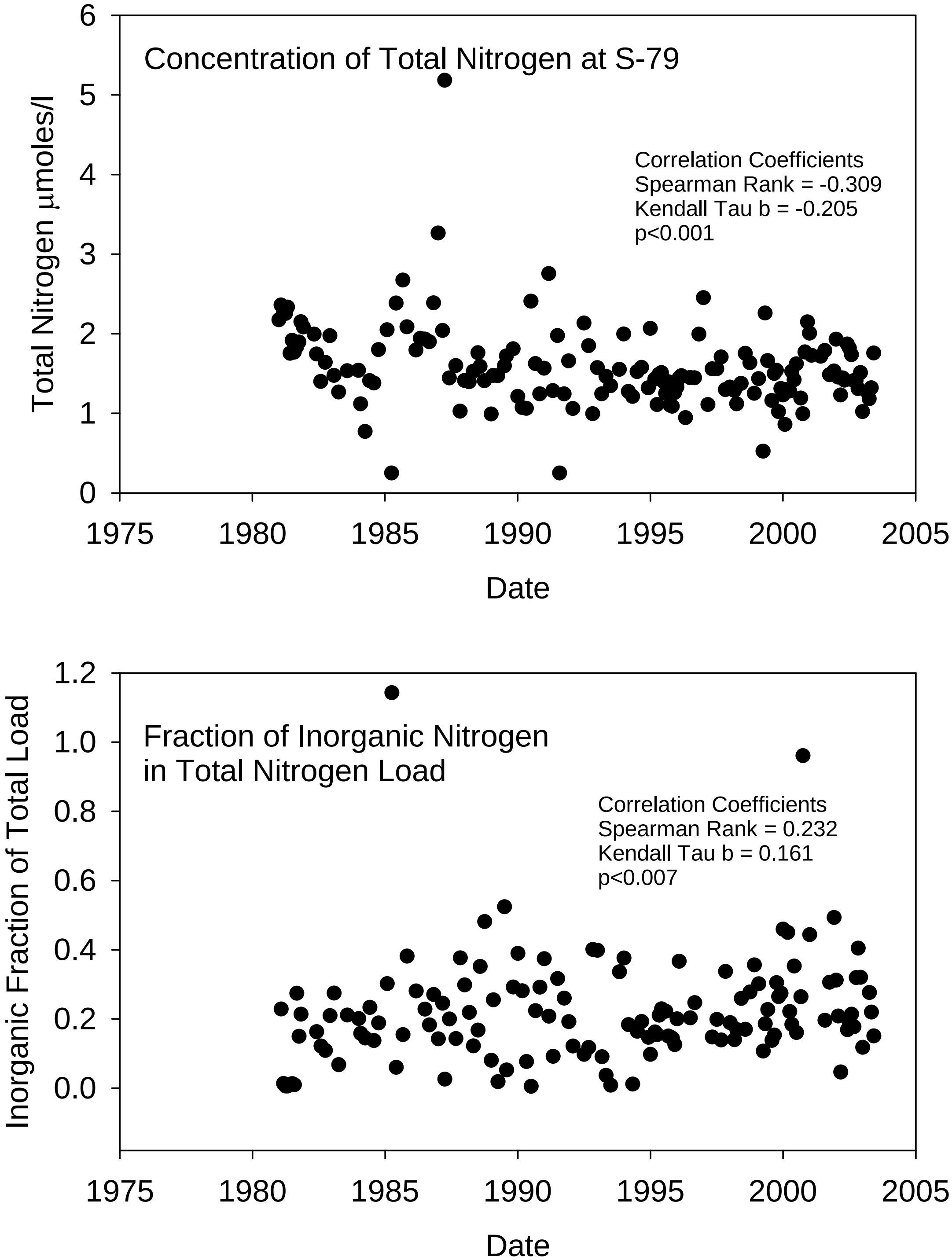

Figure 4. Trends in concentration of total nitrogen and composition of the total nitrogen load at S-79.

Trends in Concentrations of Nutrients, Chlorophyll *a* and other Estuarine Water Quality Parameters:

Evaluation of the overall spatial variation in water quality indicated several patterns Table 4). As expected, median salinity increased from the upper estuary to San Carlos Bay. Many water quality parameters showed an inverse pattern, decreasing from the upper estuary to San Carlos Bay: TN, DIN, Nitrate+Nitrite (= NOx) DIP, Color. Others such as Total Suspended Solids (=TSS) and Secchi disk depth (=SDD) followed the same pattern as salinity, increasing towards the Gulf of Mexico. Concentrations of some parameters (Chl *a*, TP,) suggested two regions of differing water quality: an upper and mid estuarine region with higher concentrations and a lower estuary- San Carlos Bay region with lower concentrations. Dissolved oxygen in bottom waters was lower in the upper estuary than in the mid and lower estuary. A minimum in the molar ratios of nitrogen and phosphorus tended to occur in the mid or lower estuary.

Evaluation of temporal trends in water quality in each region of the Caloosahatchee system is given in Tables 5a b and c. Salinity was lowest during the 1994-1996 sampling, reflecting the fact that this was a very wet period. Some of the statistical differences in water quality may be a function of this lower salinity and higher freshwater input. For example, total phosphorus (Table 5b) was higher during the 1994-1996 period than at other times. A water quality parameter was considered to show a temporal trend if the change occurred in consecutive years (e.g.: 1985-1989 < 1994-1996 < 1999-2003; 1985-1989<1994-1996=1999-2003; 1985-1989=1994-1996<1999-2003).

Total nitrogen exhibited a consistent pattern of decline in all four regions: recent concentrations measured during the 1999-2003 period were lower than those measured in the 1980s and 1990s. Dissolved inorganic phosphorus also exhibited a long-term decline with concentrations in the 1980s being higher than in the 1999-2003 period. Depending on the region, concentrations in the 1994-1996 period were either similar to the 1999-2003 period or intermediate between the 1980s and 2000s. Color increased with concentrations being lower in the 1985-1989 time period than in the 1990s and 2000s. NOx showed a similar pattern in the mid-estuary, lower estuary and San Carlos Bay. The molar ratio of dissolved inorganic nitrogen and phosphorus was lower in the 1980s than in the 1990s or 2000s. This is consistent with the decline in dissolved inorganic phosphorus described earlier. Finally, dissolved oxygen concentrations declined between the 1994-1996 and 1999-2003 sampling period in the upper and mid-estuarine regions. No temporal changes in chlorophyll *a* were detected.

Table 4. Median values of water quality parameters by estuarine region. Letters indicate statistical differences between regions at $p<0.05$. Medians with the same letter are not statistically different. SAL=salinity in ppt, TN=total nitrogen, NH4=ammonia, NOx= nitrate +nitrite, DIN=NH4 +NOx, CHL a= chlorophyll *a* in μg/l. TP=total phosphorus, DIP=dissolved inorganic phosphorus. TN_P=molar ratio of total nitrogen and phosphorus, DIN_P=molar ratio of dissolved inorganic

nitrogen and phosphorus. Units for nutrient parameters are mg phosphorus or nitrogen/l. Bot DO=concentration of dissolved oxygen in bottom waters in mg/l. Secchi disk depth is in meters, unit for Color are Pt-Co, and TSS=total suspended solids in mg/l.

Medians calculated for all three sampling periods combined except for secchi depth color and TSS. These parameters were measured in San Carlos Bay only during the 1985-1989 and 1994-1996 sampling periods.   Letters indicate statistical differences between regions as determined by the Kruskal – Wallis H test and bootstrap corrected t-tests on ranked data.

	Region			
Parameter	**Upper Estuary**	**Mid Estuary**	**Lower Estuary**	**San Carlos Bay**
SAL	4.1 d	10.1 c	22.6 b	29.4 a
TN	1.26 a	1.05 b	0.67 c	0.55 d
DIN	0.18 a	0.10 b	0.07 b	0.05 c
NH4	0.038 a	0.027 b	0.025 b	0.026 b
NOx	0.15 a	0.08 b	0.04 c	0.02 d
Chl a	10.7 a	12.7 a	5.3 b	4.2 b
TP	0.14 a	0.13 a	0.09 b	0.05 c
DIP	0.07 a	0.06 b	0.03 c	0.02 d
TN_P	5.3 a	4.7 ab	4.5 b	6.4 a
DIN_P	9.7 a	5.7 b	7.2 ab	12.0 a
BotDO	5.1 b	6.3 a	6.3 a	---
Secchi	1.05 c	1.13 bc	1.33 ab	1.37 a
Color	93 a	73 a	42 b	20 c
TSS	9.8 b	15.0 b	24.8 a	21.0 a

Table 5a. Median values for water quality parameters during three time periods in four regions of the Caloosahatchee estuarine system. Letters indicate statistical differences between periods at $p<0.05$. Medians with the same letter are not statistically different. Parameter abbreviations and units as in Table 4.

Region	**Period**	**Water Quality Parameter**					
		SAL	**TN**	**DIN**	**NH4**	**NOx**	**CHL A**
Upper Estuary	**1985 - 1989**	4.1 a	1.43 a	0.10	0.01 b	0.08	10.3
	1994 - 1996	0.3 b	1.31 a	0.17	0.04 a	0.13	3.5
	1999 -2003	1.0 a	1.13 b	0.19	0.04 a	0.10	8.6
Mid Estuary	**1985 - 1989**	13.9 a	1.30 a	0.01 b	0.01	0.002 b	8.1
	1994 - 1996	1.0b	1.29 a	0.09 a	0.02	0.06 a	7.3
	1999 -2003	8.8 a	0.91 b	0.04 a	0.01	0.02 a	10.5
Lower Estuary	**1985 - 1989**	25.3 a	0.95 a	0.01 c	0.006 c	0.005 b	4.7
	1994 - 1996	15.3 b	0.99 a	0.13 a	0.05 a	0.03 a	5.5
	1999 -2003	26.8 a	0.33 b	0.03 b	0.01 b	0.01 a	3.6
San Carlos Bay	**1985 - 1989**	30.7	0.83 a	0.01 b	0.005 b	0.002 b	3.1
	1994 - 1996	27.9	0.83 a	0.15 a	0.07 a	0.008 a	3.4
	1999 -2003	31.8	0.25 b	0.01 b	0.005 b	0.005 a	3.4

Table 5b. Median values for water quality parameters during three time periods in four regions of the Caloosahatchee estuarine system. Letters indicate statistical differences between periods at $p<0.05$. Medians with the same letter are not statistically different. Parameter abbreviations and units as in Table 4.

Region	**Period**	**Water Quality Parameter**				
		TP	**DIP**	**TN _P**	**DIN_P**	**Bot_DO**
Upper Estuary	**1985 - 1989**	0.14 a	0.08 a	4.7 b	2.7 b	6.0 a
	1994 - 1996	0.09 b	0.04 b	6.8 a	8.6 a	6.5 a
	1999 - 2003	0.13 a	0.06 b	3.9 b	5.5 a	4.0 b
Mid Estuary	**1985 - 1989**	0.12 a	0.06 a	4.3 b	0.4 b	7.4 a
	1994 - 1996	0.08 b	0.04 b	8.8 a	7.9 a	6.7 a
	1999 - 2003	0.13 a	0.04 b	3.4 c	3.4 a	5.9 b
Lower Estuary	**1985 - 1989**	0.07 a	0.04 a	5.7 a	0.95 c	7.5 a
	1994 - 1996	0.06 b	0.03 ab	7.0 a	11.7 a	6.4 ab
	1999 - 2003	0.09 a	0.02 b	1.9 b	3.5 b	5.8 b
San Carlos Bay	**1985 - 1989**	0.05	0.014 a	7.5 a	1.9 c	---
	1994 - 1996	0.05	0.014 ab	8.1 a	19.9 a	---
	1999 - 2003	0.04	0.008 b	3.0 b	5.2 b	---

Table 5c. Median values for water quality parameters during three time periods in four regions of the Caloosahatchee estuarine system. Letters indicate statistical differences between periods at $p<0.05$. Medians with the same letter are not statistically different. Parameter abbreviations and units as in Table 4.

Region	**Period**	**Water Quality Parameter**		
		Secchi	**Color**	**TSS**
Upper Estuary	**1985 - 1989**	0.94	60.4 b	7.3 a
	1994 - 1996	1.03	89.7 a	3.5 b
	1999 - 2003	1.08	88.9 a	5.8 a
Mid Estuary	**1985 - 1989**	1.07	38.3 b	12.0 b
	1994 - 1996	0.97	81.6 a	5.0 a
	1999 - 2003	1.00	64.8 a	15.5 b
Lower Estuary	**1985 - 1989**	1.26 ab	20.5 b	18.0 b
	1994 - 1996	1.06 b	51.0 a	13.3 b
	1999 - 2003	1.43 a	31.3 a	35.0 a
San Carlos Bay	**1985 - 1989**	---	---	---
	1994 - 1996	---	---	---
	1999 - 2003	---	---	---

Status of Nutrient Concentrations in the Caloosahatchee:

Since there are no numeric nutrient standards for estuaries, the status of nutrients in the Calooshatchee was assessed indirectly using the narrative nutrient standard for chlorophyll *a* of 11 ug/l. Since low concentrations of dissolved oxygen can be associated with excess nutrient loading, measured oxygen concentrations in bottom water were compared to the 4 mg/l standard for Class III, predominantly marine waters. In the upper and mid estuarine regions, monthly average chlorophyll *a* concentrations exceeded the 11 ug/l criterion over 60 % of the time (Figure 5). In the lower estuary and San Carlos Bay, the vast majority of monthly average chlorophyll *a* concentrations fell below the 11 ug/l criterion.

Dissolved oxygen concentrations in bottom waters of the upper estuary were below 4 mg/l about 35 % of the time. By contrast, somewhat less than 15 % were below the 4 mg/l criterion in the mid and lower estuary. A complete data set for dissolved oxygen in San Carlos Bay was not available.

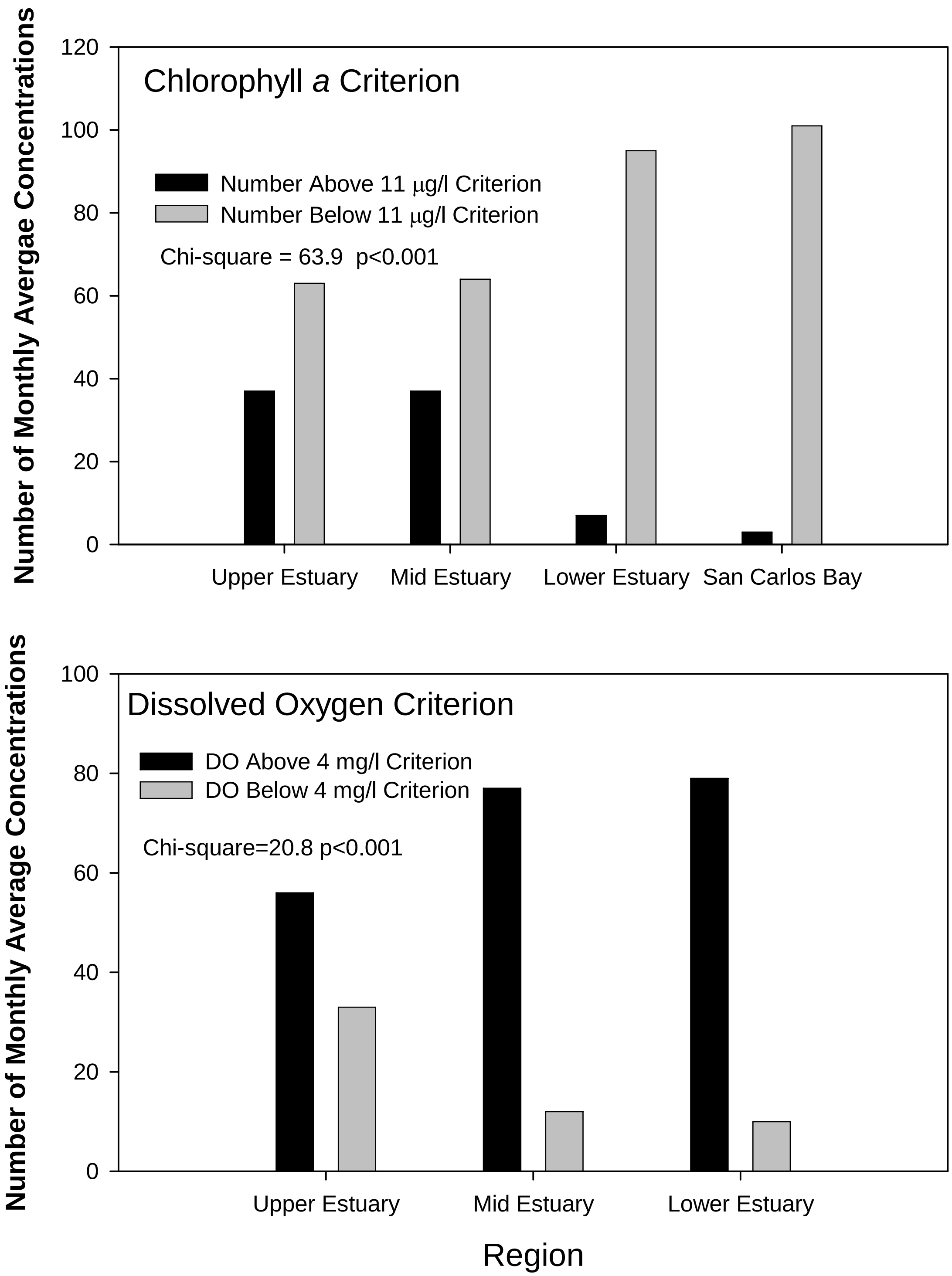

Figure 5. Number of monthly average chlorophyll *a* concentrations that were above or below the 11 µg/l narrative nutrient criterion in each region of the Caloosahatchee Estuarine System. Number of monthly average dissolved oxygen concentrations that were above or below the 4 mg/l criterion. Data include all three sampling periods.

Loading at S-79 and Nutrient Concentrations in the Downstream Estuary:

Concentrations of nutrients in downstream estuarine regions were correlated to nutrient loading at S-79 with one exception: total phosphorus in the upper estuary (Table 6). Otherwise nutrient concentrations increased as loading increased (Figures 6 and 7). As evidenced in Figures 6 and 7, loading for the 30 days prior to sampling explained less than half the variation in nutrient concentration (maximum 43% for DIN in the mid-estuary).

Table 6. Linear Pearson Correlation (r) between average nutrient concentrations measured in a region during a sampling event and the nutrient load at S-79 over the 30 days prior to sampling. The 30 day period was selected because this is the best estimate of average freshwater residence time. All coefficients are statistically significant at $p<0.05$ except where noted as ns.

	Region			
	Upper Estuary	**Mid Estuary**	**Lower Estuary**	**San Carlos Bay**
Total P	-0.041 (ns)	0.283	0.218	0.585
Total N	0.204	0.462	0.513	0.331

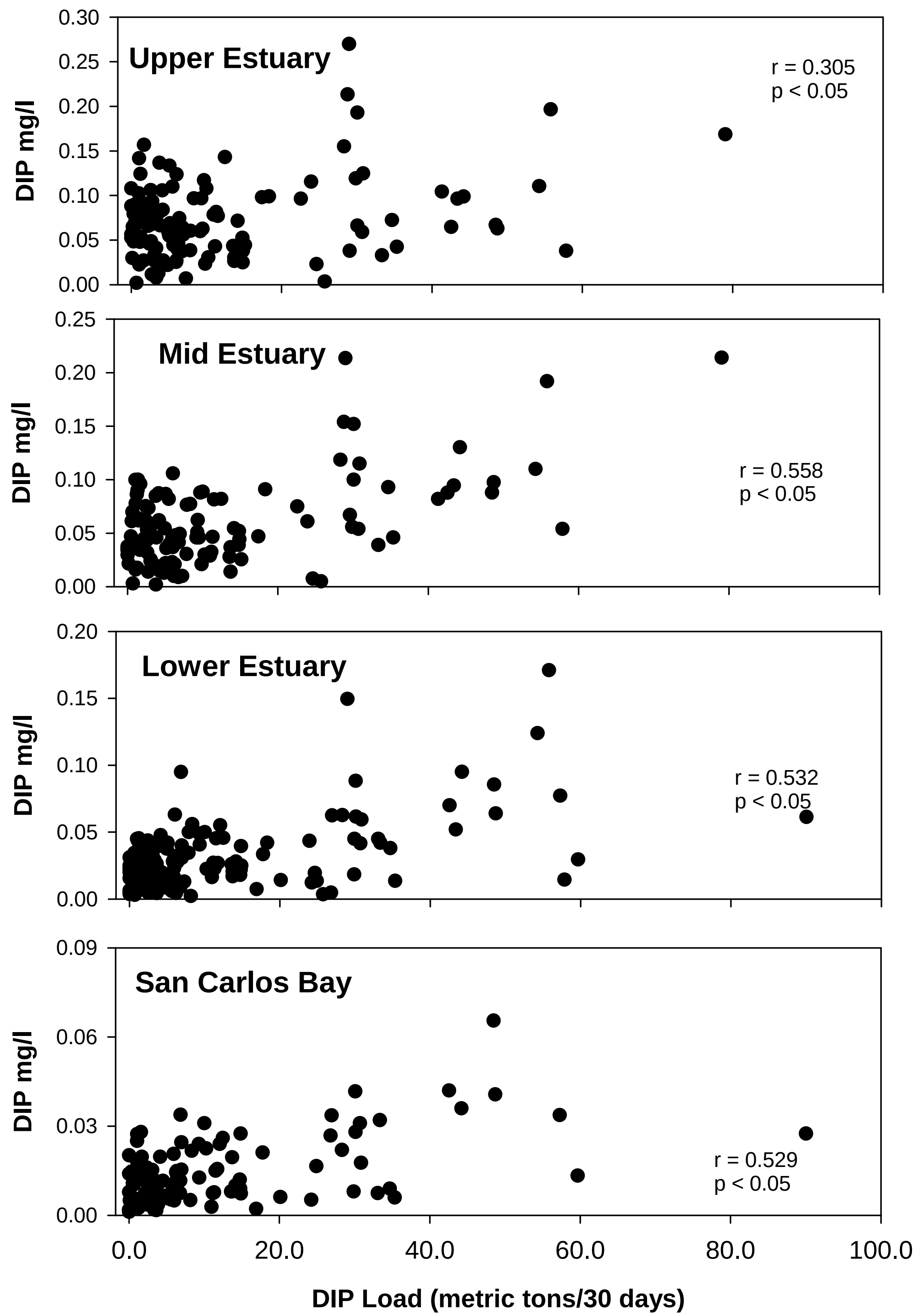

Figure 6 . Relationship between loading at S-79 and nutrient concentration in the estuary: Dissolved inorganic phosphorus (DIP).

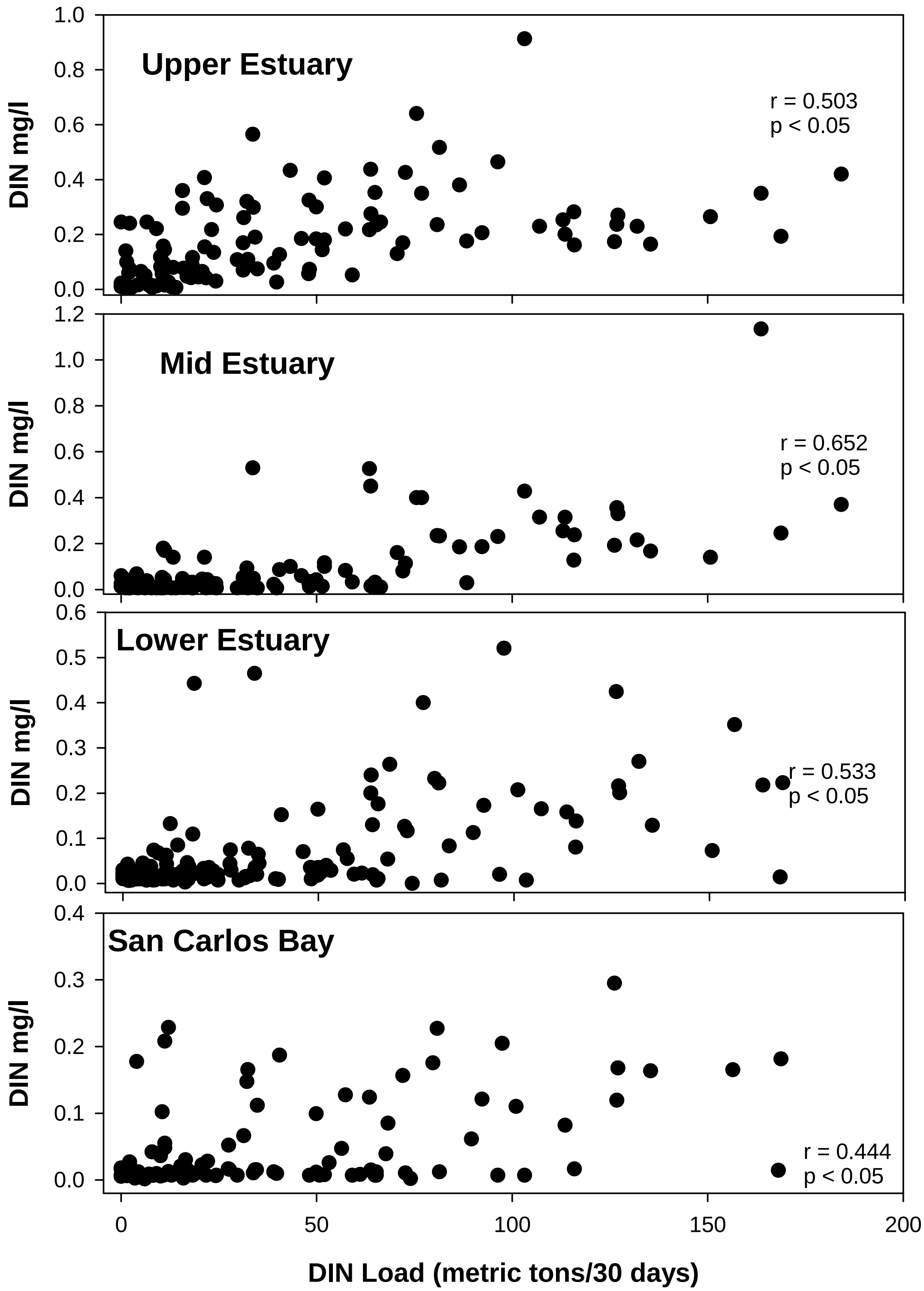

Figure 7 . Relationship between loading at S-79 and nutrient concentration in the estuary: Dissolved inorganic phosphorus (DIP).

Chlorophyll *a* as an Indicator of Eutrophication in the Caloosahatchee Estuary:

The concentration of chlorophyll *a* regularly exceeds the narrative nutrient standard of 11 μg/l in the Caloosahatchee, particularly in the Upper and Mid-estuarine regions suggesting that parts of the Caloosahatchee receive excessive nutrient loads (Figure 5). This supposition assumes (1) that chlorophyll *a* increases as a function of nutrient loading and (2) these increases lead to symptoms of eutrophication commonly associated with higher concentrations of chlorophyll, such as reduced water clarity and depressed concentrations of dissolved oxygen. These relationships are evaluated below.

Figure 7 depicts the linear correlation between chlorophyll *a* concentration in the Calooshatchee estuary and the loading of total nitrogen during the 30 days prior to sampling. The correlation varies spatially. In San Carlos Bay and the Lower Estuary increased loading corresponds to increased chlorophyll *a*. In the Mid-Estuary the correlation is not significant, suggesting that the yield of chlorophyll *a* in this region does not depend on nutrient loading. In the Upper Estuary, the relationship is negative with increased loading associated with a reduction in the concentration of chlorophyll *a*. It is worth noting that while total nitrogen loading is featured in Figure 7, this does not mean that total nitrogen limits the growth of phytoplankton in the Caloosahatchee. Chlorophyll *a* concentrations show the same regional relationships with DIN loading, DIP loading and TP loading: positive in the Lower Estuary and San Carlos Bay, not significant in the mid-estuary and negative in the upper estuary.

As noted previously, loading to the estuary at S-79 is driven by the rate of freshwater discharge. Freshwater discharge at S-79 also can explain variation in the concentration of chlorophyll *a* in the downstream estuary (Figure 9). The regional relationships are the same as those for loading: positive in the Lower Estuary and San Carlos Bay, not significant in the mid-estuary and negative in the upper estuary. In contrast to loading, there is apparent curvature in the relationships with discharge. In the mid and lower estuary and San Carlos Bay the concentration of chlorophyll *a* increased with increasing discharge up to a maximum and then began to decrease. In the mid-estuary this inflection point occurred at a 30-day average discharge of about 3000 cfs. In the lower estuary and San Carlos Bay the concentration of chlorophyll *a* began to decrease at 4300 – 4600 cfs.

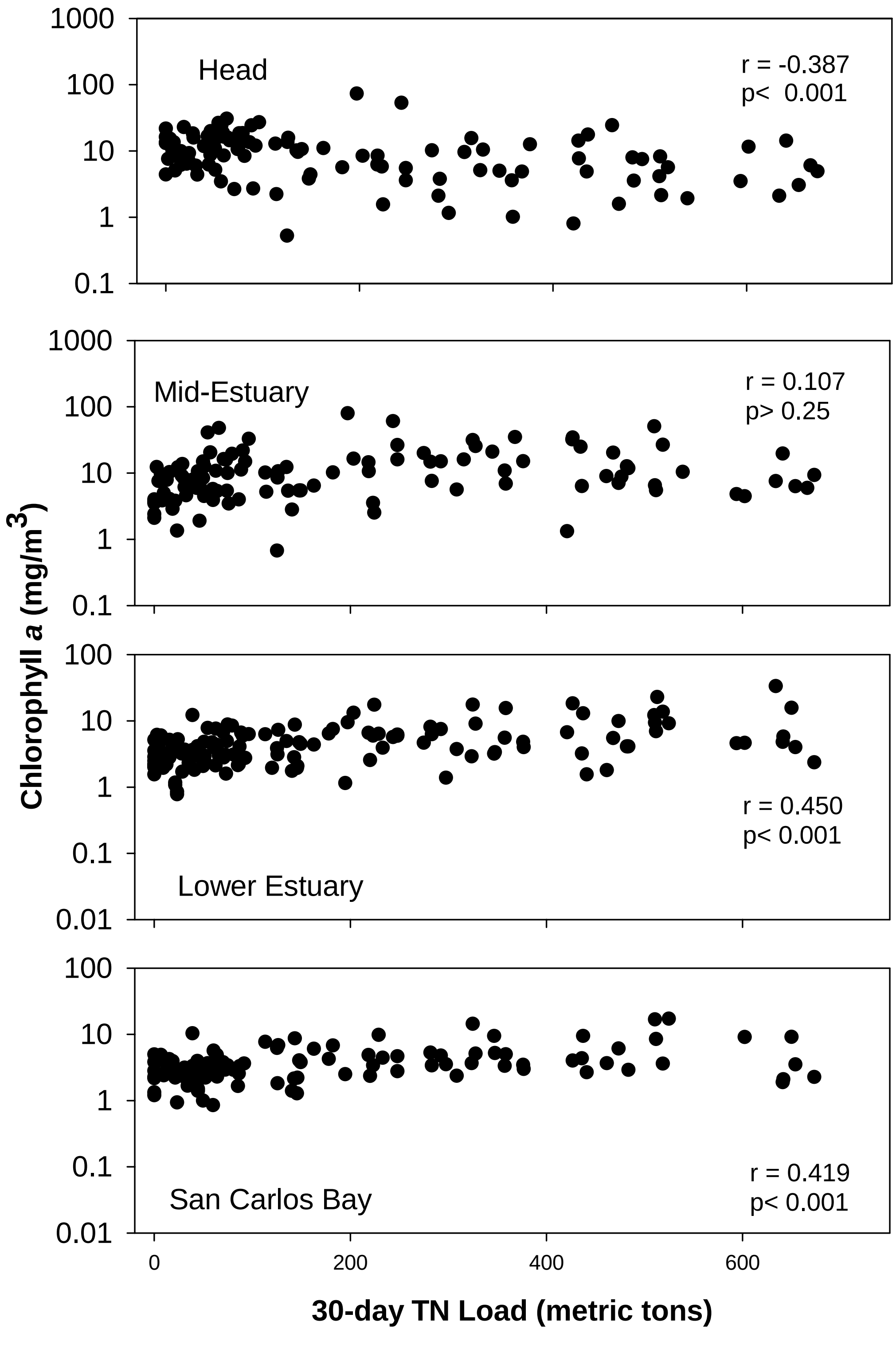

Figure 8. Concentration of chlorophyll *a* as a function of total nitrogen loading at S-79 for the 30-days prior to sampling.

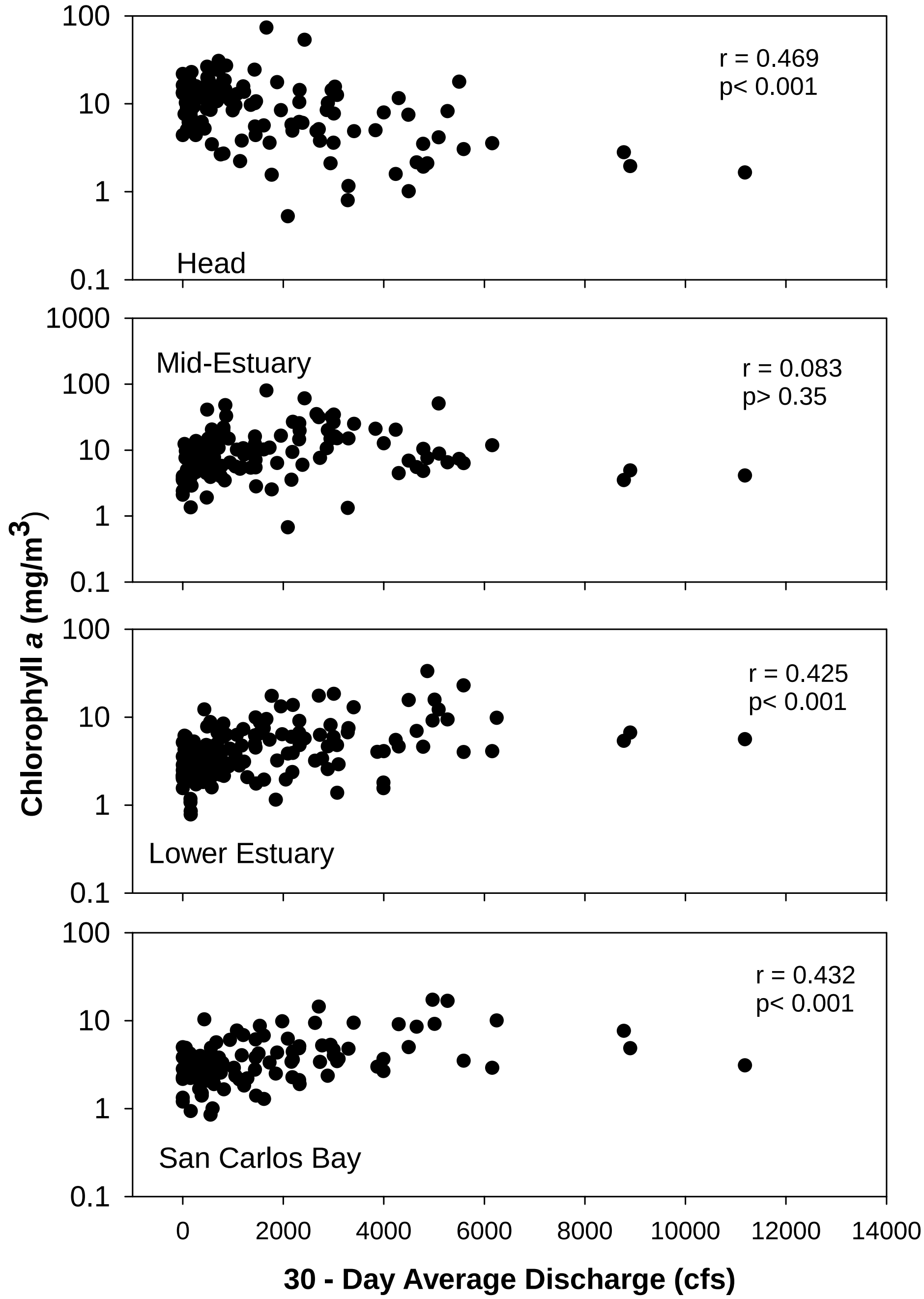

Figure 9. Concentration of chlorophyll *a* as a function of discharge of freshwater at S-79 for the 30-days prior to sampling.

Dissolved Oxygen and Chlorophyll *a* :

High concentrations of chlorophyll *a* in surface waters can be associated with low concentrations of dissolved oxygen in bottom waters (0.5 m above bottom) in the Caloosahatchee on short time scales of weeks. Such an instance is depicted in Figure 10. The crash of a chlorophyll *a* bloom coincided with a rapid decline in oxygen in bottom waters during the month of June 2000. On longer time scales, the high concentrations of chlorophyll *a* may be associated with lower oxygen concentrations one or two months in the future (Table 7).

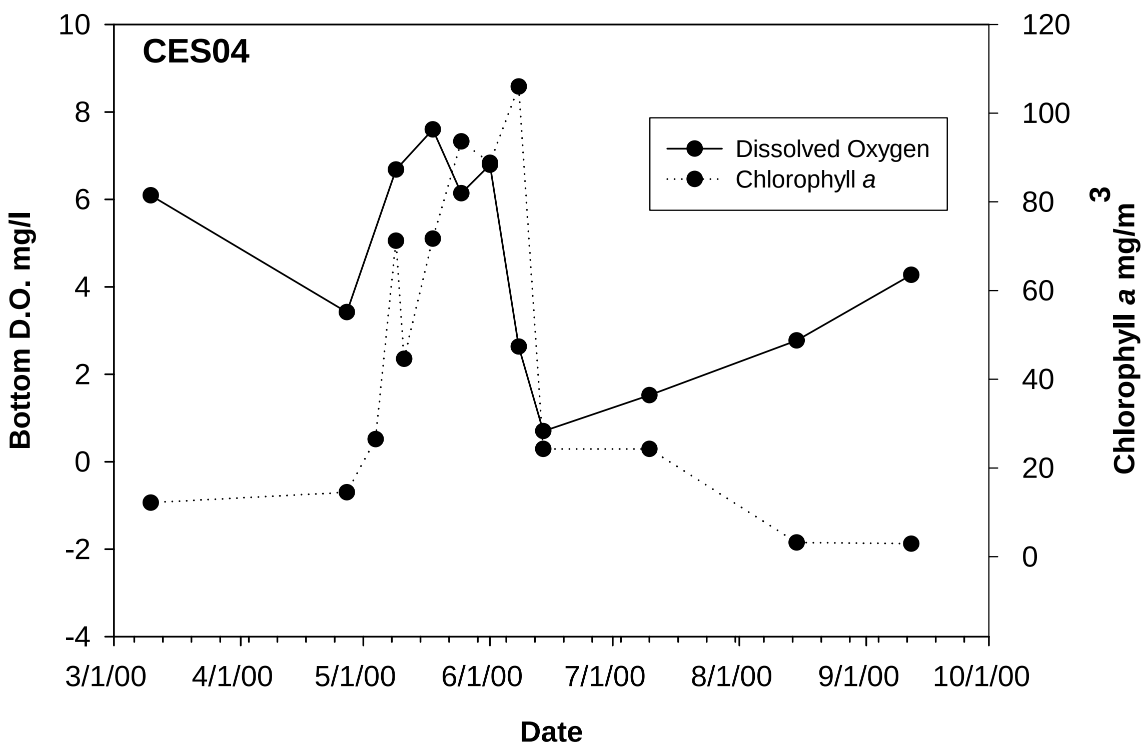

Figure 10. Time series of chlorophyll *a* and dissolved oxygen in bottom water. Note the marked decline in dissolved oxygen following a phytoplankton bloom.

Table 7. Correlation between chlorophyll *a* and the concentration of dissolved oxygen (log 10) in bottom waters. Monthly Data from CES Data Set POR: 3/99-4/2002 *p<0.05, ** p<0.01 n=33-35.

		Chlorophyll *a*		
Region	**Lag in Months**	**0**	**1**	**2**
Upper Estuary		-0.041	-0.534**	-0.633**
Mid-Estuary		0.009	-0.170	-0.359*
Lower Estuary		-0.286	-0.458**	-0.266

Chlorophyll *a* and Light Extinction:

Photosynthetically Active Radiation (PAR) data required for the calculation of the light extinction coefficient was consistently collected only during the ERD study. The results of stepwise multiple regressions relating variation in the extinction coefficient to chlorophyll *a*, color and total suspended solids are given in Table 8 . Color explained most of the variation in light extinction in the upper, mid and lower estuary. In San Carlos Bay, chlorophyll *a* explained the majority of variation.

Table 8. Fraction of total variation in the light extinction coefficient (k) explained by variation in color, chlorophyll *a* and total suspended solids (TSS) in stepwise multiple regressions. Significance level for entry in the model was $p < 0.05$ in all cases except for the Upper Estuary.

Region	**Color**	**Chlorophyll *a***	**TSS**	**Entry Level**
Upper Estuary	0.13	0.0	0.11	<0.10
Mid-Estuary	0.72	0.12	0.0	<0.05
Lower Estuary	0.78	0.11	0.0	<0.05
San Carlos Bay	0.0	0.68	0.0	<0.05

Discussion:

Nutrient Loading:

Annual loads of total nitrogen delivered to the Caloosahatchee at S-79 calculated in this study agree well with those estimated previously by Janicki Environmental (2003). Although the period of record examined here was longer than the Janicki study, agreement is remarkable for the period of overlap (1990-2003). Discharge at S-79 explained most of the variance in loading and the good agreement between studies most likely stems from the use of similar discharge data and similar methods for calculating loads.

Environmental Research and Design measure nutrient loads at S-79 intermittently during 2000 – 2002 and derived mean daily estimates for the wet and dry seasons. The ERD study shows that most of the annual nutrient load is delivered during the wet season (Table 9). The annually averaged daily loads reported here fall within the range of seasonal loads reported by ERD (2003). When an annualized daily load is derived from the ERD data, means compare well with this study (Table).

Table 9. Comparison of average daily nutrient loads (kg/day) at S-79. Annualized estimates from the ERD study are the average of the wet and dry season mean daily loads.

	ERD Study			**This Study**
	Wet Season	**Dry Season**	**Annual**	**Annual**
TN	11,051	2408	6730	7018
DIN	2476	608	1542	1385
TP	1040	355	698	657
DIP	474	211	343	426

While no long term trends in nutrient loading at S-79 were detected, some changes in concentration and composition were observed. The concentration of TN exhibited a significant long term decline at S-79. The cause is not known, this upstream decline may have contributed to the decline in TN that occurred between the 1994-1996 and the 2000-2003 sampling periods in the downstream estuary. The fraction of inorganic nitrogen in the total N load has increased over the past 20 years. This suggests that there is proportionately more N immediately available to phytoplankton in the present day load at S-79.

Long term changes in concentration at S-79 were not reflected in similar long term changes in loading. Freshwater discharge explains an order of magnitude more variation in nutrient load than concentration. Hence, long term changes in load are far more likely to reflect changes in discharge than in concentration.

The present study examined nutrient loads at S-79 only. There are other prominent nutrient inputs to the Caloosahatchee including waste water treatment facilities (WWTF). In the 1980s and early 1990s, five WWTFs discharged directly into the Caloosahatchee Estuary (Baker 1990). By 2000, the effluent from the Cape Coral plant had been reclaimed and under ordinary circumstances discharges to the Caloosahatchee had ceased.

The ERD (2003) study compared nutrient loading at S-79 with that from the remaining four plants. In general, average daily nutrient loads at S-79 exceeded those from all 4 plants combined by an order of magnitude in both the wet and dry seasons. This is not to say that loading from WWTFs is never important. During drought conditions when no flow and hence no loading occurs at S-79, WWTFs can dominate nutrient loading (ERD 2002). During drought conditions in February of 2001, of 14 freshwater inputs including tidal creeks, WWTFs, S-79 and the Orange River, the Ft. Myers South WWTF (6.1 cfs) ranked second to Telegraph Creek (6.6 cfs) in magnitude of freshwater discharge to the estuary.

Status of Water Quality:

Water quality has been a concern in the Caloosahatchee since the late 1970s and early 1980s. A waste load allocation study in the Caloosahatchee conducted by the Florida Department of Environmental Regulation concluded that the estuary had reached its nutrient loading limits as indicated by elevated chlorophyll *a* and depressed dissolved oxygen concentrations (DeGrove 1981). Target concentrations for chlorophyll *a* (20 ug/l), TN (1.0 mg/l) and TP (0.15 mg/l) were established as upper limits for acceptable water quality in the region of the estuary between Cape Coral and Beautiful Island. Similarly, McPherson and Miller (1990) concluded that additional nitrogen loading would result in increases in phytoplankton and benthic algae.

Doering and Chamberlain (1998) summarized water quality conditions in the Caloosahatchee estuary, San Carlos Bay and Pine Island Sound. Compared to other Florida Estuaries (Friedeman and Hand 19--) median concentrations of Chla and TSS were relatively low while median concentrations of dissolved oxygen, TN and color were relatively high. Turbidity and concentrations of TP were close to the statewide median values for estuaries. Like other studies of water quality (e.g. McPherson and Miller 1990; this study) concentrations of most water quality constituents decreased as proximity to clearer ocean water increased. Concentrations of TN, TP and Chla that exceeded the upper limits established by DER (DeGrove 1981) occurred mainly in the upper estuary between S-79 and Ft. Myers. Although dissolved oxygen concentration were generally high in the overall system, some values at or below 2 mg/l were observed at the head of the Caloosahatchee Estuary and these occurred in the warmer months between May and October (Doering and Chamberlain 1998). Based on Chla and dissolved oxygen, results from this study agree with the same general pattern: relatively poorer water quality in the upper estuary that improves as proximity to the ocean increases.

More recently, Janicki Environmental (2003b) examined the status and trends of water quality in the Charlotte Harbor National Estuary Program study area. Caloosahatchee estuary stations over the period 1996 – 2001 exhibited high concentrations of Chla, color, ammonia and turbidity relative to other CHNEP areas. Southern Indian River Lagoon preliminary water quality criteria for TN, Chla, SDD and TP were exceeded in 78–100 % of the samples depending on the parameter.

Trends in Water Quality:

The Janicki Environmental (2003b) report also examined trends at a number of stations in the Caloosahatchee Estuary. They detected decreases in dissolved oxygen and increases TSS and/or turbidity at a majority of estuarine stations. Some changes in concentration of one or another form of nitrogen or phosphorous were detected but there were no general trends. The significant decreases in dissolved oxygen and increases in TSS between the second (1990s) and third (2000s) periods of this study are consistent with the results of the Janicki Report (2003).

Chlorophyll *a* and Eutrophication:

In the Phase I conceptual model of eutrophication (Cloern 2001) increases in nutrient loading lead to increases in chlorophyll *a* biomass and subsequently to depletion of dissolved oxygen. Statistical analysis of data from the Caloosahatchee Estuary demonstrates that the Phase I model applies in this system. At monthly time scales, increases in nutrient loading are associated with increases in chlorophyll *a*, which in turn correspond to deceased oxygen on weekly and monthly time scales.

The Phase II conceptual model which allows for cascading secondary effects may apply in San Carlos Bay . Here, variation in chlorophyll *a* largely explained variation in light attenuation. There are extensive seagrass beds in San Carlos Bay composed primarily of *Thalassia testudinum* and *Halodule wrightii* (Chamberlain and Doering 1998). A comparison of sites in the Charlotte Harbor Estuarine system, including San Carlos Bay, showed that the depth of the deep edge of bed (DDEB) depended on light attenuation (Dixon and Kirkpatrick, 1999). The DDEB decreased as light attenuation increased. Increases in nutrient loading at S-79 correspond to increases in chlorophyll *a* in San Carlos Bay. In turn these increases can cause increased light attenuation and a shoaling of the DDEB.

Our data show that chlorophyll *a* is a good indicator of eutrophication in the Caloosahatchee Estuary – San Carlos Bay system because it is correlated with processes consistent with either the Phase I or Phase II models. Consistency with the Phase II model depends on the relationship between chlorophyll *a* and light attenuation. In this study chlorophyll *a* explained nearly 70% of the variation in k in San Carlos Bay. Elsewhere, color was most important. McPherson and Miller (1987) determined that non-chlorophyll suspended matter accounted for 83 – 92 % of light extinction in San Carlos Bay. Using data collected during 1994 – 1996, Doering and Chamberlain (1999) found that color explained variation in light attenuation throughout most of the system. In San Carlos Bay, chlorophyll *a* explained only 11 % of the variability while color explained 87%. Only at stations in Pine Island Sound, the most distant from S-79, did chlorophyll *a* explain a significant amount of variation in k (39%). At a station in San Carlos Bay near the mouth of the Caloosahatchee during 1997-98, Dixon and Kirkpatrick (1999) found that chlorophyll *a* explained only 3 % of the variation in k with color (60 %) and turbidity (37 %) being most important.

The differing results of these studies indicate that the relative importance of factors controlling light attenuation in San Carlos Bay varies. Since color is associated with freshwater, we hypothesize that freshwater discharge at S-79 determines the relative importance of color. Review of available data also suggests that the Phase II model as proposed here will apply in some years and not in others.

Critical Nutrient Loads:

If a desirable chlorophyll *a* target can be identified, then empirical relationships between nutrient loading at S-79 and chlorophyll *a* in the downstream estuary can be used to estimate a critical nutrient load. Janicki Environmental (2003a) used a standards/rule based and a reference site approach to establish chlorophyll *a* targets for the Caloosahatchee estuary of 11 μg/l and 3.8 μg/l respectively. An alternative approach is to use a resource based approach to identify chlorophyll *a* targets using the light requirements of seagrasses. Assuming that seagrasses require 20% of incident daily photosynthetically active radiation (PAR) for growth, the chlorophyll *a* –light attenuation relationship can be used to estimate the chlorophyll *a* concentration associated with the DDEB. The nutrient loading - chlorophyll *a* relationship can then be used to estimate critical loads. This approach is illustrated in Table 10 and is based on the following equations.

Equation 1:

Chlorophyll *a* (μg/l) = -10.54 – 14.57 * (-K)
$R^2 = 0.68$ $p<0.05$

where K is the diffuse light extinction coefficient.

Equation 2:

TNmt30 = 66.72 + 32.59 * Chlorophyll *a* (μg/l).
$R^2=0.17$ $p<0.05$

Where chlorophyll a is the average concentration measured in San Carlos Bay on a sampling date and TNmt30 is the total nitrogen loading that occurred over the 30 days prior to the sampling date in metric tons.

Table 10. Critical Loads of Total Nitrogen required to achieve an adequate supply of light (20% of incident) to support growth of seagrasses at various depths.

Depth (m)	**K (20%)**	**Chl a (μg/l)**	**30 Day TN (mt)**	**Annual TN (m)t**
0.5	-3.219	36.66	1261	15,138
1.0	-1.609	13.20	497	5,964
1.5	-1.073	5.49	242	2,910
2.0	-0.805	1.49	115	1,383

No critical loads for S-79 have been adopted. It should be noted that while critical load estimates can be derived from equations 1 and 2, the estimates themselves will not be particularly reliable or useful for management because Equation 2 above has such a low R^2. Nevertheless it is worth while to compare critical loads calculated here with those estimated by Janicki Environmental (2003a). They provided two chlorophyll *a* targets: a standards/rule based estimate of 11 μg/l and a reference system based estimate of 3.8 μg/l. According to Equation 1 above a chlorophyll *a* concentration of 3.8 μg/l would allow 20% of incident light to reach a depth of 1.6 meters. A concentration of 11 μg/l would allow 20 % incident light to reach 1.09 meters.

The load associated with a chlorophyll *a* concentration calculated using Equation 2 yields a somewhat higher load than the empirical relationships developed by Janicki Environmental (2003). The reference system based chlorophyll *a* concentration of 3.8 μg/l is associated with a wet season load of 39 mt of total N/month and a dry season load of 0 mt total N/month (Janicki Environmental 2003a). The standards/rule based 11 μg/l concentration is associated with a dry season load of 172 mt total N/month and a wet season load of 318 mt total N/month. Estimates for the 3.8 μg/l and 11 μg/l targets using equation 2 are 191 mt total N/month and 425 mt total N/month respectively and closer to the wet season loads predicted by Janicki Environmental (2003a).

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